

A Survey of Perceptual Feedback Issues in Dexterous Telemanipulation: Part I. Finger Force Feedback

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Abstract¹: The goal of this paper (Part I of II) is to identify and analyze some specific requirements on the design of dexterous master devices meant for teleoperating multifingered robotic hands, within the context of finger force feedback. The requirements are of 2 categories: *constructional* and *functional*. The constructional issues consist of the isomorphism, portability, motion range capability, and accommodation for human hand size variability. The functional issues consist of the bandwidth compatibility with the human hand, which itself has asymmetric input/output characteristics, the proprioceptive (force limit) compatibility, and the consideration of the psychometric stability of the human hand in sensing force magnitudes and variations. Also of importance is the sensitivity of the master device that must be more than that of the human hand. In this regard, 14 existing designs of hand masters have been evaluated to see how well they satisfy the afore stated constructional and functional requirements.

1 Introduction

1.1 Why Multifingered Hands?

In most instances of teleoperation, reported to date, the slave will be a serial link manipulator equipped with a parallel-jaw gripper as its end effector. The human operator will be provided with a switch for opening and closing the gripper in order to grasp and ungrasp the desired objects during task execution. Such grippers, however, have 3 major limitations in view of advanced telemanipulation tasks:

- Only those objects with parallel and plane surfaces can be comfortably grasped. But, objects of arbitrary

shapes with uneven surfaces cannot be grasped easily.

- Small reorientations of the object cannot be performed by the gripper alone. Hence, the entire slave arm has to be moved. Making fine motions by moving the entire slave arm is often difficult and time consuming due to the dominant effects of inertia and friction.
- Structural properties of the grasped object, such as the surface smoothness cannot be inferred via such grippers. Humans however, find such information to be extremely useful when handling delicate objects.

All three problems can be overcome by equipping the slave arm with an end effector capable of emulating human hand like motions and sensing abilities. Such capabilities exist in multifingered robotic hands. For literature on existing multifingered robotic hands, see works by Hanafusa and Asada (1977), Crossley and Umholtz (1977), Okada (1982), Lian et al (1983), Salisbury (1985), Kobayashi (1985), Rovetta (1985), Jacobsen et al (1986), Kim et al (1987) and Van Brussel et al (1989) among others. Typically, the hands are 3-4 fingered and are actuated by electric, hydraulic or pneumatic means. Recently, the importance of using such hands as the slave end effectors is being increasingly recognized by the telemanipulation community (Bejczy 1977; Clark et al 1989a, 1989b; Burdea and Speeter 1989; Burdea 1989).

1.2 Why Dexterous Masters?

The use of robot hands as slave end effectors raises the problem of using appropriate master devices for control. In principle, one could use instrumented joysticks in a way similar to a classical teleoperator controller. In reality, however, such joysticks are totally inadequate in sensing and transmitting the dexterous and agile motions of a human hand. The most appropriate master devices for this purpose are the instrumented gloves (VPL, 1991) or the exoskeletons (Exos, 1991) that can precisely sense and transmit the motions of the human hand, Figure 1. Such devices are generically referred to as **dexterous hand masters** in this paper. These hand masters will have two main functions:

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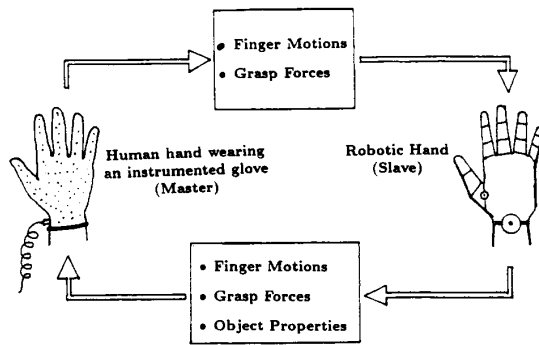


Figure 1: A telemanipulation scheme using a multifingered robotic hand as the slave end effector and using an instrumented glove or a hand exoskeleton as the master controller.

- to measure the movements of the human operator's finger joints and send them to the slave hand, and
- to receive the perceptual information from the slave hand and present it to the human operator's fingers such that the human operator feels as if he was performing the task himself instead of the remote slave hand.

The former is a basic requirement as in any teleoperation process. The latter is useful in providing the human operator with a sense of presence at the remote cite. Such an illusive sensation has been referred to the literature as the telepresence (Fisher, 1986), tele-existence (Tachi et al, 1991), virtual reality (Stone, 1991) and cyberspace (Foley, 1987). In order to provide the human operator with a sense of telepresence, adequate perceptual information must be fed back to the operator. This perceptual information, typically, constitutes the visual, auditory, force, touch and in some cases vibrations too. Table 1² presents a list of some recent works wherein one or more of these perceptual informations were feedback in applications involving teleoperation, telepresence, teleprogramming and virtual reality. However, this paper is concerned only with two specific issues: the **force feedback** (Part I) and the **touch feedback** (Part II) in relevance to such applications.

1.3 Why Force Feedback to Fingers?

In the context of using multifingered robot hands as slaves, there are two types of forces that must be feedback to the human hand: *the wrist forces* and *the finger (grasp) forces*. The issue of feeding back the wrist forces has been addressed by several researchers who were using parallel jaw grippers for object handling. Their approaches are equally valid in the present context as well. Their results show that, just feeding back the wrist force itself leads to:

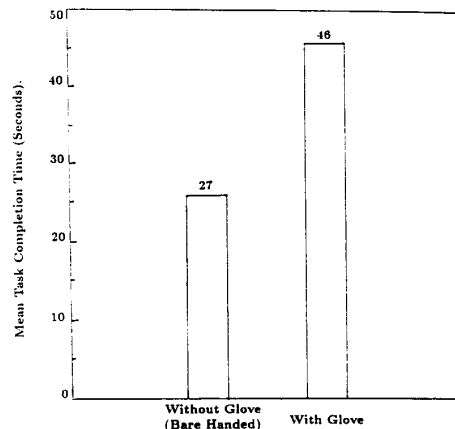


Figure 2: A comparison of the completion time of a peg-in-hole task performed by humans with and without wearing a space suit (non-sensorized) glove. Data from Chodack and Spampinato (1991).

- a reduction in task completion time (Hannaford and Wood 1989; Draper et al 1987; Massimino and Sheridan 1989),
- a reduction in energy consumption (Hannaford and Wood 1989),
- a reduction in number of errors during the task (Hannaford and Wood 1989; Draper et al 1987), and
- a reduction in magnitudes of the contact forces (Draper et al 1987).

From the same view point, when using a multifingered robotic hand as the slave end effector, providing the human operator with a feedback sensation of the grasping forces exerted by the slave fingers would positively enhance the operator's abilities. This is evident from the results of the "peg-board dexterity test" recently reported by Chodack and Spampinato (1991) aimed towards the design of gloves to go with the space suits. When 4 subjects wore gloves, the time taken for a peg insertion task increased by 80% in comparison to bare hands, Figure 2. This increase is attributed to the stiff gloves that prevented the subjects from precisely sensing the actual grasping and insertion forces. This result implies that the finger force feedback to the human operators hand in a telemanipulation task is not only desirable but could be crucial in tasks involving precise manipulation of delicate objects. With such an ability, the operator would be better placed to judge the task status and better predict the necessary grasping and manipulation forces. Consequently, the tasks are performed relatively quickly and with improved quality.

² All tables are on the next page.

Table 1: Perceptual informations feedback to the human operator in some existing telepresence experiments.

Year	Researchers	Perceptual Feedback					Intended Application
		Vision	Sound	Force	Touch	Vibration	
1984	Tachi et al.	•					Telepresence
1984	Minsky	•		•			Virtual World
1985	Tachi and Arai	•					Telepresence
1987	Fisher et al.	•			•		Telepresence
1987	Hightower and Spain	•					Telepresence
1987	Zimmerman et al.	•			•		Virtual World
1988	Tachi et al.	•			•		Telepresence
1988	Quek et al.	•					Virtual World
1988	Pepper and Kaomea	•					Virtual World
1989	Tachi et al.	•	•	•	•	•	Telepresence
1989	Crane et al.	•		•			Telepresence
1990	Iwata	•		•			Virtual World
1990	Brooks Jr. et al.	•	•	•			Virtual World
1990	Minsky et al.	•		•	•		Virtual World
1990	Bejczy et al.	•		•			Teleoperation
1991	Tachi et al.	•	•	•			Telepresence
1991	Stone	•			•		Telepresence
1991	Puttre	•	•	•		•	Virtual World
1991	Ling	•	•		•		Telepresence
1991	Funda and Paul	•		•			Teleprogramming
1992	Burdea et al.			•			Teleoperation

Table 2: General Features of the dexterous hand masters used in the literature for teleoperation or for interacting with virtual environments.

Name of the Device	constrn. material	weight (kg)	No. of Fings.	No. of Joints	Fitting Hands		Finger Joint Position Sensor			Source Reference
					Male	Female	Type	RSN(J)	B/W(I)	
1. Z-Glove	Cloth	Light(i)	5	10	most	?	Similar to the DataGlove			Zimmerman (1987)
2. Oomichi Device	Plastic	?	4	4	most	?	?	?	?	Oomichi (1987)
3. Utah Device†	(j)	1.5	2	3	95%	95%	pot ^b	analog	10 kHz	Jacobsen et al (1989)
4. Iwata Device	Al	3.0 ^a	3	3	80%	50%	pot ^b	0.6 ⁰	40 Hz	Iwata (1990)
5. Jau/JPL Device	Cloth	1.1	4	16	most	?	pot ^b	?	?	Jau (1990)
6. Portable Master	Plastic	0.045	2	2	most	most	LVDI	?	20 Hz	Burdea (1991)
7. Grip Master	Plastic	?	(c)	(c)	95%	5%	Hall	0.5 ⁰	100 Hz	Exos (1991)
8. Hand Master	Plastic	0.35	5	16-20(h)	95%	5%	Hall	0.5 ⁰	100 Hz	Exos (1991)
9. Sato Device	Rubber	V. light	5	(d)	most	most	Provides touch feedback only			Sato et al (1991)
10. Teletact	Acrylic	0.125	5	?	95%	95%	Provides touch feedback only			Stone (1991a)
11. DataGlove	Lycra	0.1	5	10+6(e)	3 sizes (f)		fiber optic	1 ⁰	60 Hz	VPL (1991)
12. Mattel Glove †	Rubber									Mattel (1992)
13. New Master	Plastic	0.15	3	3	most	most	Uses DataGlove			Burdea et al (1992)
14. CyberGlove	Lycra	0.1	5	22	99%	99%	RBS (g)	?	100 Hz	Virtual (1992)

(a): Includes the weight of the Stewart platform.

(b): Potentiometer

(c): Measures wrist motion only.

(d): Only the tips are sensed but not the joints.

(e): 6 additional degrees are the position and orientation of the wrist.

(f): Custom sizes also available in addition to 3 standard sizes.

(g): RBS - Resistive Bend Sensor.

(h): Possible to vary the no. of sensed finger joints.

(i): Very light but its weight unknown.

(j): Derlin, Aluminium, and Steel.

(k): RSN - Resolution.

(l): B/W - Bandwidth.

Table 3: Features related to the finger force feedback ability of the existing dexterous hand masters in the literature.

Name of the Device	Force Sensing	Force Feedback	Force Feedback				Portability
			Actuator	Resolution	Range	Bandwidth	
1. Z-Glove	x	x	-	-	-	-	Excellent
2. Oomichi Device	•	•	Electric	?	?	?	Good
3. Utah Device	•	•	Hydraulic	Analog	?	10 kHz	Good
4. Iwata Device	x	•	Electric	?	3.3 N	4 Hz	Good
5. Jau/JPL Device	•	•	Electric	?	?	?	Good
6. Portable Master	•	•	Pneumatic	0.05 N	22 N	10-20 Hz	Very Good
7. Grip Master	•	x	-	-	-	-	Very Good
8. Hand Master	x	x	-	-	-	-	Very Good
9. Sato Device	x	x	-	-	-	-	Very Good
10. Teletact	x	x	-	-	-	-	Excellent
11. DataGlove	x	x	-	-	-	-	Excellent
12. Mattel Glove	x	x	-	-	-	-	Excellent
13. New Master	•	•	Pneumatic	0.05 N	22 N	10-20 Hz	Very Good
14. CyberGlove	x	x	-	-	-	-	Excellent

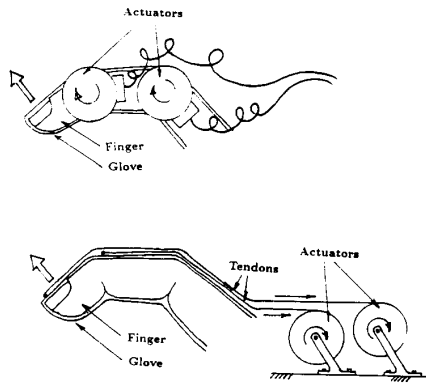


Figure 3: Two approaches to placing the actuators for exerting reaction forces to the human operator's fingers: (a) actuators right at the finger joints, (b) actuators placed remotely and connected via tendons.

The issue of feeding back the finger forces, though in principle similar to the wrist force feedback, brings in new complexities. The main content of this paper is to analyze the specific problems, to evaluate the existing solution approaches, and to finally present a new approach to overcome some existing drawbacks. Also pointed out are some unresolved research issues as related to the problem of finger force feedback within the context of dexterous telemanipulation.

2 Master Requirements in View of Force Feedback

2.1 Constructional Requirements

The primary requirement is that both the hand master and the slave robotic hand are kinematically identical to the human hand and hence be mutually isomorphic. That is, the link dimensions, the motion and torque ranges of the joints of the hand master and the slave hand be identical. Consequently, the transformation of parameters from the slave to the master or back will be one-to-one.

In the process of feeding back the slave finger forces on to the operator's hand, the reaction forces to his fingers are exerted by actuators. These actuators could either be placed right at each finger joint or be placed remotely while the force is transmitted to the finger joints, Figure 3. The former approach leads to a bulkier hand master which in turn may reduce finger motion ranges and add counter balancing problem. The latter approach, however, could reduce the portability.

Two other requirements that are important to hand masters with force feedback are the following (Bergamasco et al, 1991). One, the hand master, either the glove-type or the exoskeleton-type, must be designed to have enough strength, particularly where the human finger experiences the reaction force resulting from finger force feedback. Second, the device must allow for the variabil-

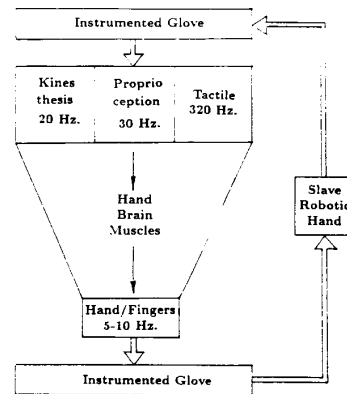


Figure 4: The asymmetric input/output capabilities of the human hand in applying and sensing the finger tip forces. Data from Brooks (1990).

ity of the human hand so that several operators could use the same hand master without sacrificing too much on the accuracy or the precision of measurement. Otherwise, the reflected force on the fingers gets scaled up or down according to the hand size and hence leads to imprecise perception of the interaction forces.

2.2 Functional Requirements

An important functional feature of a hand master is its bandwidth. It is the frequency with which, it can receive the motion commands from the human operator and provide the force feedback to the operator's fingers. It is clear from the literature (Brooks, 1990) that the human hand has asymmetric input/output capabilities, Figure 4. That is, the maximum frequency with which a typical human hand can transmit motion commands to the hand master is 5-10 Hz while it demands that the position and force feedback signals be presented to it at a frequency not less than 20-30 Hz, Figure 4. If the operator wishes to feel high frequency low amplitude force commands such as a tool chatter at the slave end, the force feedback to the operator's fingers must be provided at about 300 Hz. However, the earlier work by Sharpe (1988) indicates that the feedback to the operator's hand be provided at no less than 500 Hz in a typical task while a feedback frequency of 5-10 kHz may be necessary in a precision task. On the contrary, Brooks (1990) reports that the human hand cannot discriminate between two force signals at frequencies above 320 Hz and hence perceived as just vibrations. To resolve this issue, unfortunately, no concrete experimental evidence is available. Nevertheless, it is clear that the bandwidth requirement depends upon the nature of the task. To facilitate the operator choose a bandwidth, a few available numerical values have been listed in Figure 5.

The experimental results by Wiker et al (1989) show that the operator fatigue and discomfort are aggravated

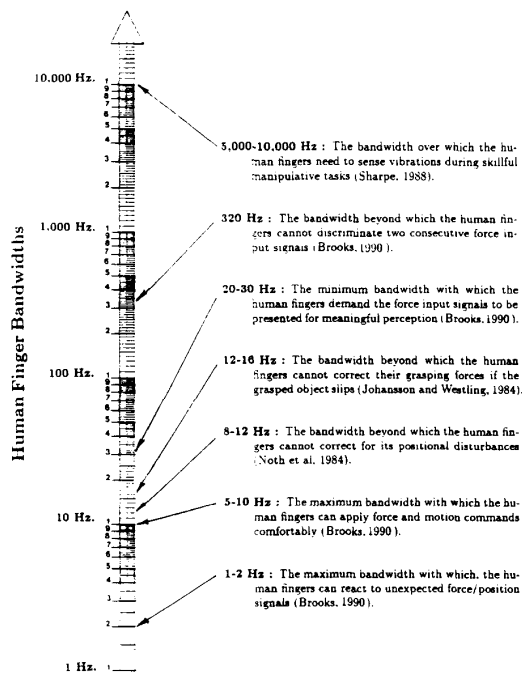


Figure 5: The human hand uses different bandwidths for different tasks. Following are some figures reported in the existing literature. An ideal hand master to dexterous telemanipulation must be able to work over the entire wide range of bandwidths if it has to be useful for both normal and skillful telemanipulation tasks.

by two factors: the grasping force and the work-to-rest ratio. The result is the loss of operator's ability of estimate force magnitudes and variations. However, the operator comfort will be within safe levels if the grasping (or reflected/reaction) forces are less than about 15% of the maximum exertable force (maximum force: 30-50 N, Sutter et al, 1989). That is, the index, middle and the ring fingers can safely exert about 7, 6, and 4.5 Newtons respectively without encountering fatigue and discomfort. If larger levels of forces must be exerted, then the work-to-rest ratio must appropriately be chosen as per the scheme given in Wiker et al (1989). If these ground rules are violated, the operator may tend to misjudge his finger forces and hence can cause task failure.

To have an effective feedback of the finger forces in a hand master, the sensitivity of the hand master must also be considered. The human fingers, for example, can sense force variations of 0.5 N (Taylor, 1968). Further, if this load is distributed, the sensed pressure must not be below 0.2 N/cm² which is the minimum pressure that a human finger can sense (Gruppen et al, 1989). The hand master, therefore, must be equal to or more sensitive than the human hand in sensing and feeding back the finger forces.

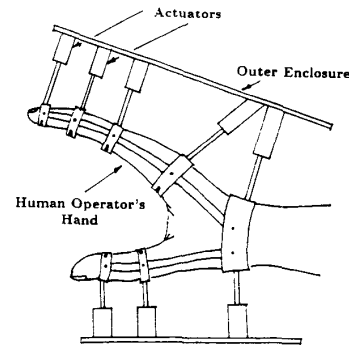


Figure 6: The dexterous hand master with force feedback, proposed by Zarudiansky (1981).

3 Existing Dexterous Masters with Force Feedback

This section analyzes the constructional and the functional features of the existing masters that have the force feedback ability, in order to evaluate how well they satisfy the requirements outlined in the last Section. The general features of 14 such masters have been summarized in Table 2. Notably, from further details in Table 3, only 6 hand masters have the finger force feedback ability.

3.1 Constructional Aspects

An early dexterous master with finger force feedback was perhaps that by Zarudiansky (1981), Figure 6. This, however, is not listed in Tables 2 and 3 as no technical data is available at this time. The device consists of a conical enclosure within which the human operator's fingers and wrist were connected to the actuators that apply reaction forces back to the fingers and wrist. The contact forces sensed at the slave hand were used to apply reaction forces on the corresponding phalanx. This master device, though isomorphic to its slave, has severely restricted portability. It is further unknown if it allows for the human hand size variability.

A complete hand-arm system was built by Jacobsen et al (1989) where each joint on the master experiences the reflected force from the slave. To be noted here is that all joints on the master coincide with the human joints. The master device has only 3 fingers while the slave has 4 fingers and hence they are mutually unisomorphic. It is argued however that only 3 fingers are sufficient to perform most routine tasks. The force feedback is applied to the human joints via high performance hydraulic actuators. The system is too bulky to be portable as it includes the entire master for the arm-hand system. Consideration for human hand variability is assumed subjected to recalibration.

A compact portable master for 2-fingered slave was developed by Burdea (1991), Figure 7. The device consists of a linear variable differential transducer (LVDT) to mea-

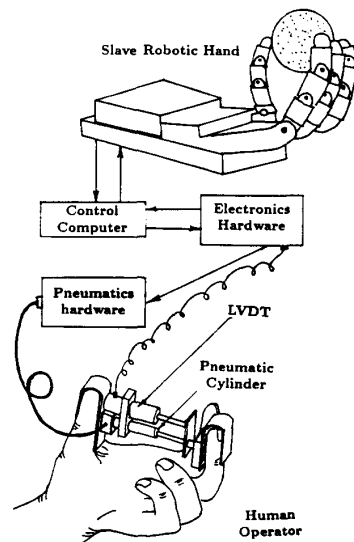


Figure 7: A compact portable force feedback master suitable for 2-fingered slave, built by Burdea (1991). The master, consisting of a mini pneumatic cylinder and an LVDT, has been used for teleoperating slaves with more than 2 fingers too (Burdea and Speeter, 1989).

sure the relative positions of the two master fingers while a pneumatic (cylinder) actuator was used to exert the reaction force to the operator's fingers. The device is very portable, light weight and allows for hand size variability. The 2-fingered master was used, with some cleverness, to demonstrate the force feedback from a 4-fingered Utah/MIT hand as the slave (Burdea and Speeter, 1989; Burdea and Zhuang, 1991).

A 4-fingered 16-jointed electrically actuated hand master was built at JPL by Jau (1989, 1990, 1992). In this system, the reaction forces to the finger joints are applied via remotely located electric motors via flexible cables. The overall system seems to be bulky while it is claimed to have been designed for portability. Male hand size variations are considered in the design.

A compact desktop master with 9 degrees of freedom was built by Iwata (1990) for interaction with virtual worlds. Of the 9 dofs, the device used 6 dofs for positioning the wrist itself (3 positions + 3 orientations). The remaining 3 dofs are used for the tip of the thumb, index and middle fingers where the ring and little fingers work with the middle finger itself. The device is good for inputting hand gestures rather than using as a master in telemanipulation. It has a restricted work volume because of the way it is designed. Because it is an experimental device, the design does not seem to have been accounted for hand size variability.

Recently, Burdea et al (1992) has designed a 3 fingered dexterous master. Here, the actuators for exerting reaction forces to the fingertips are similar to the ones used earlier by Burdea (1991), while the position sensing is now

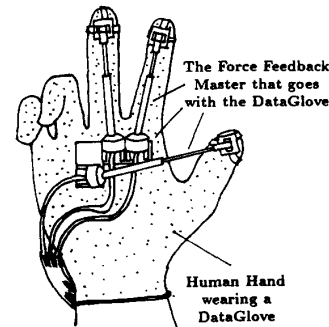


Figure 8: The new portable force feedback master suitable for 3 or more fingered slave, built by Burdea et al (1992). Each actuator in this master is similar to the one earlier used in Burdea (1991). The new master is meant for using with a position sensing glove such as a DataGlove.

performed by a DataGlove (VPL 1992). The arrangement of the actuators in this master is shown in Figure 8. This device, like its predecessor, is light weight, portable and allows for human hand variability. Experiments have been performed using the device for interaction with virtual objects. Towards the same goal, Andrenucci et al (1989) proposes a tendon actuated system where the reaction force is exerted on the operator's fingers by kevlar tendons driven by remotely placed electric motors in a way similar to that shown earlier in Figure 3b. However, issues of friction and compliance in such systems remains to be addressed.

3.2 Functional Aspects

The bandwidth of a dexterous hand master is an important aspect in view of its speed of operation. As was discussed in Section 2.2, the human hand can provide command inputs to the master at only about 5-10 Hz while the force feedback signals to the human fingers must be presented at at least about 20-30 Hz. For a satisfactory performance, the recommended control bandwidth is about 10 times the minimum necessary bandwidth (Brooks, 1990). That means, the master's sensory activity – measuring joint angles, rates and forces must be performed at not less than 100 Hz while the force feedback to the human fingers be at not less than 300 Hz. If the operator wishes to feel vibrations at the slave fingers, the force feedback needs to be performed at not less than 3 kHz.

Although several dexterous masters with force feedback have been built and used (Table 3), very few provide details on the bandwidth of the system. The pneumatic actuators used in the 2-fingered master, designed by Burdea (1991) and later used in the 3-fingered master designed by Burdea et al (1992) work at 20Hz max., which is about $\frac{1}{15}$ of the recommended bandwidth. This means, the operator can feel the reflected forces from the relatively slow routine tasks but not the high frequency low amplitude forces such as the ones that occur in vibration or chatter-

ing. The actuator can exert a maximum of 22 Newtons with a precision of ± 0.05 Newtons. The system's rise time is about 50-100 milliseconds which is manageable. The only other negative point about the device is that the functional ranges of some finger joints are reduced up to 50% because of the nature of the design.

The compact desk-top master built by Iwata (1990) can apply a maximum reaction force of about 3.5 Newtons on each finger and can work at about 4 Hz which is very slow. Since the actuators that apply the reaction forces are electric, the speed of response of the device as a whole could have been better but the actual cause for this slow response is not reported.

Similar data on the other force feedback masters is currently unavailable.

4 Conclusion

The main conclusions of this paper, as related to the finger force feedback issues, are as follows.

- Of the 14 designs of existing hand masters detailed in the literature (Table 2), only 6 are capable of feeding back the grasping and manipulating forces of the slave fingers on to those of the human operator (Table 3).
- None of the existing hand masters, capable of finger force feedback, are truly isomorphic to the human hand.
- A few hand masters are portable while many are bulky.
- It is clear that the human hand has asymmetric input/output capability in view of commanding and sensing fingertip forces. It can output force commands at 5-10 Hz. while it requires the slave fingertip forces to be presented as input the human hand by the master device at 20-30 Hz. Chattering could only be felt if signals are presented to the hand within the range of 300-400 Hz. while the corresponding bandwidth for fine vibrations is 5,000-10,000 Hz. An ideal hand master must be able to use all these bandwidths in accordance with the situation.
- Human fingers can exert 30-50 Newtons for brief periods while they can sustain only 4-7 Newtons for sustained periods without affecting their ability to sense the force magnitudes and variations. An ideal hand master must be able to scale up the hand force output and scale down the reflected force to fingers whenever necessary so that the human operator can apply sustained large forces (only the slave end) without losing his psychometric stability of force sensing.
- Human fingers can sense a force step of about 0.5 Newtons or a pressure variation of about 0.2 N/cm^2 . The hand master must have at least 10 times better sensitivity than that of the human hand.

Future designs of hand masters must take the above factors into account in order to enable the human operator feel the remote or the virtual environment. So that, he can perform telemanipulation of objects with improved dexterity and hence achieve a higher degree of success.

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